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**ARTICLE**

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**Can the tinnitus spectrum identify tinnitus subgroups?**

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**Abstract**

The tinnitus spectrum is a psycho-acoustic metric of tinnitus. Previous work found a tight relation between the spectrum and the tone audiogram. This suggests that the spectrum and the audiogram provide essentially the same information, and the added value of the spectrum is limited. In order to test whether the spectrum shows tinnitus characteristics that cannot be inferred from the audiogram, we re-examined the relation between the tinnitus spectrum and the tone audiogram, in a group of 80 tinnitus patients. We defined three subgroups of patients, using the shape of their tinnitus spectrum: (1) patients with a spectrum, monotonously increasing with frequency (2) patients with a distinct peak in their spectrum, (3) all other patients. Patients in group 3 typically showed low frequency tinnitus spectra. In all three groups, the largest hearing loss was at high frequencies (>2 kHz). The mean audiograms of group 1 and 2 were remarkably similar; group 3 had an additional hearing loss for the lower frequencies (<2 kHz). The three groups did not differ with respect to age, sex, or tinnitus questionnaire outcomes. In subgroups 2 and 3, the shape of the spectrum clearly differed from that of the tone audiogram. In other words, the spectrum technique provided information that could not have been obtained by tone audiometry alone. Therefore, the spectrum measurement may develop into a technique that can differentiate between classes of tinnitus. This may eventually contribute to the effective management of tinnitus, as various classes of tinnitus may require different therapeutic interventions.

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**Full Text**

**Introduction**

Tinnitus is a very common disorder. People with tinnitus hear a sound that is not related to any sound source outside the body. In most cases, there is not even an acoustical sound source inside the body, despite the fact that the sound may be perceived "in the ear" or "in the head." Then, it must be assumed that the tinnitus is a phantom percept, based on neuronal mechanisms instead of an acoustical source.

Like other phantom percepts, it is a considerable challenge to determine the characteristics of the tinnitus in a subject. A typical approach is to have subjects match the percept of an external stimulus to that of the tinnitus. For example, the amplitude and frequency of a tone can be varied such that its percept matches the tinnitus. This results in a matched amplitude and frequency. There are some limitations to this procedure. The reproducibility of the result is limited. [1] In addition, in many cases, tinnitus is not perceived as a simple tone and it is questionable to what extent the tone reflects the tinnitus. Finally, tinnitus is often associated with hearing loss. Thus, the percept of a particular matched tone may be quite different to the subject with tinnitus from that of a normal hearing investigator wanting to interpret the pitch and

loudness of the matched tone.

A relatively new method to identify the characteristics of tinnitus is the tinnitus spectrum test. [2],[3],[4] The test is a procedure to determine the perceptual characteristics of tinnitus following a well-described protocol. Subjects are presented with stimuli of a range of frequencies, respectively. Each stimulus is rated with respect to its likeliness to the tinnitus. This procedure results in a plot of likeliness versus frequency, which is termed the tinnitus spectrum. The shape of the tinnitus spectrum displays a remarkable resemblance to the tone audiogram: Stimuli with frequencies for which a hearing loss exists display a larger likeliness than stimuli for which the hearing threshold is (near) normal. This suggests that the spectral content of the tinnitus resembles that of the hearing loss.

Although the similarity of the tinnitus spectrum and the tone audiogram is of great interest, it appears to limit the clinical applicability of the tinnitus spectrum measurement. If the spectrum and the audiogram are similar in shape, it could be argued that the spectrum can be predicted from the audiogram or vice versa. They would essentially provide the same information. This prompted us to make a detailed study of the correspondence between spectrum and audiogram. If the correspondence is very tight, it must be concluded that the spectrum has no additional value for diagnostic purposes. However, if in a subclass of patients, the spectrum and audiogram are dissimilar, the spectrum appears to provide additional information that could not have been revealed with the audiogram alone. Then, the spectrum has an added value.

In this paper, we confirm that the tinnitus spectrum has a shape that is similar to the tone audiogram. However, in an initial evaluation of our data, we noted a remarkable subdivision in cases of high-frequency hearing loss: In some patients, the stimuli with the highest frequency were judged to be less similar to the tinnitus than lower-frequency stimuli. In these patients, the tinnitus spectrum clearly deviated from the audiogram. This suggests that the tinnitus spectrum contains information that is not present in the tone audiogram. We decided to group our patients based on characteristics of the tinnitus spectrum, to evaluate whether the differences between the spectra reflected any other patient characteristics.

## Methods

Eighty subjects with chronic tinnitus were included [Table 1]. Their age varied from 17 years to 75 years, with a mean of 52 years. The tinnitus duration varied from 1 year to 27 years, with a mean of 6.1 years. There were 55 male and 25 female participants. The tinnitus lateralization was right-sided in 32 subjects, left-sided in 22 subjects and bilateral or central in 26 subjects. Four subjects (2/1/1, in group 1/2/3, respectively) had pulsatile tinnitus. In none of these cases, a vascular cause of the tinnitus was found. All subjects underwent standard tone-audiometry at the octave frequencies from 250 Hz to 8000 Hz and an assessment of the tinnitus spectrum as part of a clinical protocol. The protocol also included the Tinnitus Handicap Inventory (THI) [5] and the Hospital Anxiety and Depression Scale (HADS) questionnaires. [6] {Table 1}

The tinnitus spectrum measurement was performed in a manner similar to Roberts et al, [3] Subjects were seated in soundproof booth, in front of a computer screen. All acoustic stimuli were generated on a Tucker-Davis 3 system and presented via Telephonics THD49 headphones. The computer screen displayed a user interface that contained instructions and sliders, as relevant during the course of the test session. Subjects used a turning knob (Powermate USB multimedia controller, Griffin Technology) to control the sliders on the screen. The knob could also be pushed, which was used to confirm a response. The measurements were controlled by a custom-built Matlab computer program.

During an initial phase of the test, subjects learned to use the turning knob. They were shown that they could control sliders on the computer screen by turning the knob. Furthermore, the knob was used to control the loudness of an acoustic stimulus, in order to familiarize them with the perceptual loudness concept.

After the initial training phase, all subsequent stimuli were presented at the tinnitus ear in the case of lateralized tinnitus and at the right ear for non-lateralized tinnitus. Subjects were first presented with three narrowband stimuli, centered at 3 kHz, and were asked which of the three mostly resembled their tinnitus. The first stimulus was referred to as "hissing." It consisted of Gaussian noise that was digitally filtered with a second-order band pass Butterworth filter with a width at -3 dB that equaled 10% of the center frequency. The second stimulus was referred to as "ringing," and was similar to "hissing," except that the bandwidth was only 3% of the center frequency. Finally, the third stimulus was a pure tone. In the subsequent procedures, only the stimulus type that was chosen by the subject was presented (hissing, ringing or tone), although the procedure involved variation of the center frequency.

In the next step, the loudness of stimuli presented at nine frequencies (0.25; 0.5; 1; 2; 3; 4; 5; 6; and 8 kHz), respectively, was matched to the loudness of the tinnitus. Subjects could match the loudness of the external stimulus by turning the control knob, and confirmed their choice by pushing the knob. For each frequency, the matching procedure was performed 3 times.

Finally, stimuli were presented at the nine frequencies, respectively. At each stimulus frequency, the stimulus was presented three times at the average tinnitus-matched intensity (obtained in the previous step). For each stimulus, the subjects were asked to rate to what extent the sound stimulus was present in their tinnitus (in Dutch, the question displayed on the screen was: "Komt dit geluid voor in uw tinnitus?"/"Is this sound present in your tinnitus?"). They indicated the likeliness on a Borg CR100 scale presented on the computer scale. They could control the position of a slider along the scale by turning the knob, and confirmed their response by pushing the knob. This provided three likeliness ratings for each of the nine test frequencies. The entire tinnitus spectrum test was performed in about 20 min.

## Results

Three repeated measurements of loudness and likeliness were taken in each patient at each test frequency. The test-retest variability was computed as a standard deviation. [Figure 1] displays the distribution of standard deviations (SD) of the loudness and likeliness measures. Subjects were able to reproduce loudness matched within 5 dB in 81% of the measurements. The reproducibility was similar across all test frequencies. The SD of the likeliness was within 20 points in 82% of the measurements. There was no obvious relation between test frequency and SD of the likeliness as investigated with a two-way repeated measures ANOVA.{Figure 1}

Subjects were grouped with respect to their tinnitus spectrum. We defined a 20-point downward drop between the peak of the tinnitus spectrum and the likeliness at 8 kHz to be a relevant decrease in likeliness. Group 1 consisted of the individuals where the tinnitus spectrum was a monotonously increasing function of the test frequency. In some cases, there was a small likeliness drop at the higher frequencies, but this drop was smaller than the 20 points threshold value. In group 2, the tinnitus increased monotonously up to a certain frequency, beyond which there was a drop of at least 20 points in likeliness. Finally, group 3 included all remaining subjects. These subjects typically had a tinnitus spectrum that decreased with increasing test frequency. [Figure 2] shows examples of typical subjects of each of the three patient groups. For each subject, the tinnitus spectrum as well as the audiogram is displayed.{Figure 2}

The three groups did not differ with respect to age, male/female ratio, tinnitus loudness, tinnitus annoyance, THI score and HADS score [Table 1]. Furthermore, the distribution of tinnitus qualities (tonal, ringing, and hissing) and tinnitus lateralization was not significantly different between the groups. Thus, despite the fact that the tinnitus spectra differed, all these other characteristics were similar across the three groups.

[Figure 3] displays the median tinnitus spectra of the three groups. Consistent with the definition of the groups, the spectrum in group 1 is a monotonously increasing function, and in group 2 the spectrum slopes down at higher frequencies. The remaining group 3 displayed a median spectrum that slopes down with increasing frequencies. Here, low-frequency test stimuli resembled the tinnitus better than high-frequency stimuli.{Figure 3}

[Figure 4] displays the audiograms of the three groups. In all three groups, the largest median hearing loss was present at high frequencies (>2 kHz). The two groups with a predominantly high-frequency tinnitus spectrum (Groups 1 and 2) had remarkably similar audiograms. Group 3, that had a low frequency tinnitus spectrum, displayed a mild median hearing loss at low frequencies, in addition to the high-frequency loss.{Figure 4}

For each subject, the Pearson correlation coefficient between the likeliness and the hearing threshold was calculated. [Figure 5] shows a box and whisker plot of the correlation coefficients for each group. There is a large spread in correlation values, although most subjects show a positive correlation, typically indicating a patient where increasing likeliness corresponds with increasing hearing loss. Median correlations equaled + 0.80, +0.55, -0.09, for groups 1, 2, and 3, respectively. The median values of all three groups differ significantly from each other, as tested with a Mann-Whitney U-test ( $P < 0.05$ ).{Figure 5}

The relation between the peak of the tinnitus spectrum (the frequency at which the likeliness was largest) and the peak in the audiogram (the frequency of the maximum hearing loss) is shown in [Figure 6]. When the maximum value was reached at two frequencies, the highest frequency was taken. For 57 out of 80 patients (71%), peaks differed one octave or less. In group 1 and 2, the tinnitus spectrum most frequently peaked at a frequency between 1/4 and 3/4 octave below the maximum hearing loss. The mean peak difference for group 1 was - 0.07 (SD 0.8) oct; for group 2: -0.09 (SD 1.5) oct; and for group 3: -2.6 (SD 2.9) oct. The peak differences of group 3 differed significantly from the other two (t-test, two-sided,  $P < 0.01$ ).{Figure 6}

When comparing subjects with an absolute peak difference larger than one octave with subjects with a smaller peak difference, the first group had worse hearing thresholds. This was especially the case for the hearing thresholds at lower frequencies (0.25-1 kHz): the average thresholds were 17 and 31 dB, for the subjects with a peak difference up to, and more than one octave, respectively (t test:  $P = 0.0029$ ). There was a weak correlation ( $r = +0.29$ ) between average hearing threshold up to 1 kHz and the absolute peak difference ( $P = 0.0088$ ). So, subjects with worse low frequency

hearing showed a larger deviation between threshold and tinnitus spectrum.

## Discussion

We showed that the tinnitus spectrum has important similarities to the audiogram. In subjects with a high-frequency tinnitus spectrum (group 1 and 2), the audiogram indicated a high-frequency hearing loss. This confirms the previous findings by Norena et al, [2] König et al, [7] and Roberts et al. [3] However, for the subjects with high-frequency tinnitus, there may be two perceptual classes. In one group (group 1), the tinnitus likeliness increased with frequency over the entire frequency range. In another group (group 2), there was an optimum frequency (at 5 kHz in the group median tinnitus spectrum, [Figure 3]b), and the likeliness decreased towards higher frequencies. At this point, it is unclear whether group 1 and 2 correspond to two separate tinnitus classes. The criterion to define group 1 and 2 (a 20-point drop in likeliness) was rather arbitrarily chosen. However, our analysis emphasizes that in a number of tinnitus patients (group 2) the likeliness clearly decreases toward higher frequencies.

These results seem consistent with a recent study by Sereda et al, [8] who showed that in a subgroup of tinnitus patients, the tinnitus pitch is on the edge of the audiogram. Our group 2, with tinnitus at the slope of the audiogram, may correspond to their edge group. One neurophysiological theory of tinnitus [9] predicts that tinnitus will be at the edge of the audiogram. Our results suggest that this neurophysiological model can be applied to a subgroup of tinnitus subjects. However, the largest group of tinnitus patients [8] (group 1 in this paper) are not consistent with the edge theory. A candidate mechanism to explain the results in this group would be homeostatic plasticity, which has been hypothesized to result in tinnitus within the hearing loss frequency range. [10] The increase in spontaneous and stimulus induced neural activity in the auditory centers after sensory deprivation is hypothesized to result from homeostatic up regulation of neural activity, which aims at maintaining the mean neural activity around a set-point. In this theory, tinnitus is generated by an increase in spontaneous activity in the auditory centers in the frequency range of the hearing loss, consistent with the finding in group 1 of our study population.

Group 3 consisted of patients in which the lower frequencies were primarily present in the tinnitus percept. Interestingly, this group also had a high-frequency hearing loss, although they had an additional loss for the lower frequencies. This group demonstrates that the tinnitus does not always occur near the frequency of maximum hearing loss. Instead, the tinnitus percept may be related to a mild low-frequency hearing loss. The comparison of the peak values of the spectrum and the audiogram [Figure 6], showed that on average the tinnitus pitch was 2.6 octaves below the maximum hearing loss. The fact that we found a rather large number of patients (20%) that could not be attributed to group 1 or 2, may reflect the fact that patients were selected from a specialized out-patient tinnitus clinic in a tertiary referral center (in our department). We speculate that this may have biased our patient population.

The partial dissociation between the audiogram and the tinnitus spectrum (in groups 2 and 3) shows that the spectrum technique provides information that could not have been obtained by tone audiometry alone. Therefore, the spectrum measurement may develop into a technique that can differentiate between classes of tinnitus. This may eventually contribute to an effective management of tinnitus, as various classes of tinnitus may require different therapeutic interventions.

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